Preliminary observations of global ocean mass variations with GRACE

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[1] Monthly estimates of the Earth's gravitational field from the GRACE mission are used to construct a time-series of global mean ocean mass variations between August 2002 and December 2003. This time-series is compared to a mean climatology determined from satellite altimeter measurements of global mean sea level corrected for the steric variation. The GRACE observations show a seasonal exchange of water mass with the continents of the same magnitude (~8.5 mm) and phase (maximum in early- to mid-October) as the steric-corrected altimetry. This is one of the first direct validations over the ocean of the primary GRACE science mission to measure time-variable transports of water mass in the Earth system, and it suggests that GRACE data can be used to measure non-steric mean sea level variations which is important for climate change studies. *INDEX TERMS:* 1655 Global Change: Water cycles (1836); 1836 Hydrology: Hydrologic budget (1655); 4556 Oceanography: Physical: Sea level variations. **Citation:** Chambers, D. P., J. Wahr, and R. S. Nerem (2004), Preliminary observations of global ocean mass variations with GRACE, *Geophys. Res. Lett.*, *31*, L13310, doi:10.1029/2004GL020461.

1. Introduction

[2] It is known that the Earth's oceans, atmosphere, and land exchange water mass as part of the hydrological cycle via precipitation, evaporation, freezing, melting, and runoff. Although the total amount of water in the Earth system is constant, the amount in any component (atmosphere, oceans, soil moisture, glaciers, ice sheets, etc.) can vary significantly over time. The ocean and continents are the largest reservoirs, with only a relatively small amount being stored in the atmosphere. When averaged globally, there is a large seasonal exchange of water mass between the oceans and land, which has been measured directly with satellite altimetry corrected with a climatological steric model [*Chen et al.*, 1998; *Minster et al.*, 1999; *Cazenave et al.*, 2000]. Satellite radar altimeters observe the total sea level variation, including the signal caused by temperature and salinity fluctuations (the steric effect) and non-steric barotropic and mass variations. After removing the steric variation from the altimeter sea level measurements and averaging globally, the residual is interpreted as the eustatic, or mass variation.

[3] Although altimeter missions like TOPEX/Poseidon (T/P) and Jason-1 observe the total global mean sea level (GMSL) variation every 10-days, determining the global steric variation at the same frequency is impossible. There are not enough in situ measurements in a 10-day period to sample the global oceans; it is difficult enough to collect sufficient data in 1- or 5-year periods to compute global steric variations [*Levitus et al.*, 2000]. Instead, the steric variation is computed from monthly average grids of temperature and salinity profiles determined from decades of in situ data, such as the World Ocean Atlas (WOA) climatologies [e.g., *Stephens et al.*, 2002]. This limits one to studying only the seasonal water mass cycle in the oceans. Previous studies have all shown that the ocean mass variation is significant, with annual amplitudes between 7 and 9 mm of water, and a maximum in late-summer, early-fall [*Chen et al.*, 1998; *Minster et al.*, 1999; *Cazenave et al.*, 2000].

[4] The GRACE Mission was designed to measure changes in the Earth's gravity field caused by water mass moving among the components of the Earth system. A description of the mission and its present status can be found in *Tapley et al.* [2004]. In the following sections, we discuss the computation of the water mass time-series, and we compare the two calculations (GRACE and steric-corrected altimetry) to assess the ability of GRACE to observe the global water cycle.

2. Data Processing

2.1. Altimetry and Steric GMSL

[5] We use data from the TOPEX altimeter on T/P for January 1993 to July 2002, and data from the Jason-1 altimeter for August 2002 to December 2003, giving 11 years of continuous altimeter observations of global mean sea level along the same groundtrack. Besides applying the normal geophysical and atmospheric corrections, we include corrections for a drift in the TOPEX microwave radiometer and a new sea state bias model [*Chambers et al.*, 2003a], and remove a global bias of 15 cm to align the Jason-1 data with TOPEX [*Chambers et al.*, 2003b]. An inverted barometer (IB) correction is not applied to the data, since the IB model used to correct the altimetry is

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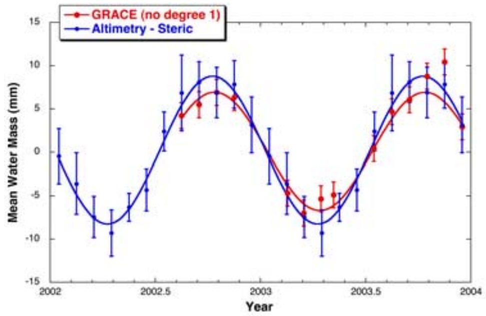

Figure 1. Mean ocean mass variation (in mm of water) computed from seasonal altimetry and steric GMSL (blue), and GRACE (red). The GRACE measurements do not include degree 1 terms. The thick blue and red lines are the best-fit annual sinusoid. The error bars on the altimetry – steric time-series are based on 95% confidence level on the altimetry mean, accounting for interannual variations.

constrained to be zero for a global average and we find that it averages to less than 0.5 mm RMS between ±66°, the latitude limits of the altimeters. GMSL variations are computed directly from the 1-sec along-track sea level anomalies as described in *Nerem* [1995], and averaged over exact months. A mean monthly climatology is computed by first removing a bias and 11-year trend from the record, then averaging over the 11 values for January, February, etc.

[6] The steric variation is computed from the most recent World Ocean Atlas 2001 (WOA01) grids [*Stephens et al.*, 2002]. The steric variation at each grid point and month is computed from changes in the ocean density field computed from the temperature and salinity values to 1500 m depth and an equation of state (see *Jayne et al.* [2003] for formulation). The 1° maps of steric sea level anomalies are then averaged over the oceans between ±66° latitude. The average is area-weighted similar to the altimetry. When the steric GMSL climatology is subtracted from the total GMSL climatology from altimetry, there is a clear seasonal variation (Figure 1). While our amplitude (8.8 mm) is similar to the previous estimates [*Chen et al.*, 1998; *Minster et al.*, 1999; *Cazenave et al.*, 2000], our maximum phase (278°) occurs approximately a month later. This is mainly due to our longer altimetry time series, which better averages through the large 1997–1998 ENSO event.

2.2. GRACE

[7] GRACE does not measure gravity field or mass variations directly, but instead measures changes in range between the two GRACE spacecraft. These range variations are used to estimate a set of spherical harmonic coefficients representing the gravity field each month. Thus, the GRACE data represent a spatial averaging of the mass variations, and not a point measurement. Although the time-variable gravity field is estimated to spherical harmonic degree and order 120 (wavelength ~300 km), the expected errors are significantly larger than the time-variable signal except at the longest wavelengths. *Swenson and Wahr* [2002] describe a method to compute mean water mass variations over a specific region using an averaging kernel that has a value of ~1 inside the region and ~0 outside the region, and constructed to minimize the errors in the mass recovery. We use this method to compute the ocean mass variations by constructing an averaging kernel over the global oceans. This is a slightly different averaging area than the coverage of the altimetry and steric observations (±66°), and the consequences are discussed in the next section. The mean ocean water mass is expressed in mm of equivalent water thickness so that it directly corresponds to the non-steric GMSL measurements from the altimetry and steric observations.

[8] We use "monthly" sets of the gravity coefficients distributed by the GRACE project via PODAAC to the Science Team for August–November, 2002, February–May, 2003, and July–December, 2003. A solution for April/May 2002 is available but is not used because the data processing may not have handled several in-flight activities that occurred during the time-period (S. Bettadpur, personal communication, 2004) and it stands alone in time without nearby solutions. The coefficients are not necessarily estimated over exact monthly intervals due to data outages and the groundtrack of the GRACE satellites. The time stamp we assign to the GRACE average is the mid-point of the exact time interval used to compute the coefficients. GRACE is sensitive to the water mass variations in the ocean, land, and in the atmosphere below it. However, a model of the atmospheric gravity signal determined from the ECMWF model as well as a barotropic model forced by ECMWF winds and pressure is used in the GRACE processing as part of the background force model, along with other effects such as ocean tides, solid earth tides, and others. Thus, the gravity field coefficients are the observed variation relative to these background models. If the models are accurate, then the signals have been effectively removed, and the GRACE products measure the time-variable gravity excluding the atmosphere, tides, etc. If the models are not accurate, then the GRACE data will contain the true variation corrupted by the model error. An important part of the GRACE calibration/validation effort is to assess if there are indications of errors in the background force models.

[9] The barotropic model used in the processing is known to have problems at monthly periods (V. Zlotnicki, personal communication, 2003), as it is designed mainly to predict the ocean's barotropic variability at periods of a few days. Thus, one should restore the monthly average of the model heights to any maps determined from the GRACE fields. However, the barotropic model is mass conserving, so that a global average of the model output is always zero; water mass is just exchanged within the model so there is no globally average error, only local ones. We have confirmed that the average of the model used for GRACE is approximately zero. Thus, the GRACE average ocean mass variation calculation is not affected by the barotropic model.

[10] The GRACE data are not corrected for the pole tide over the ocean, but the altimetry is. So to be consistent, we apply a pole tide correction to the GRACE results using the same model used for the altimetry [*Wahr*, 1985]. We also add back the secular rates for the degree 2 terms that were removed as a background model in the GRACE processing, since this is not done in the altimetry. The GRACE monthly gravity field models do not include estimates of the degree 1 geopotential coefficients, which describe the movement of the Earth's center-of-mass in an Earth-fixed reference frame

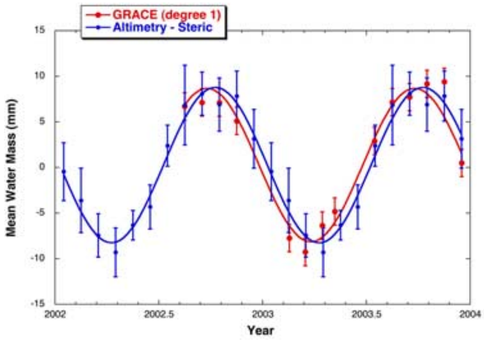

Figure 2. Similar to Figure 1, except the GRACE measurements include degree 1 terms.

(the geocenter), since the GRACE measurements are relatively insensitive to these long-wavelength gravity variations, and the GRACE frame of reference is chosen to be the instantaneous geocenter. However, including degree 1 terms is important if one is looking at just one component of mass variability, since the geocenter variations arise from transporting mass among and within the ocean, land, and atmosphere [*Wahr et al.*, 1998]. Since we are interested in using GRACE to compute an independent, gravity-based estimate of the total water mass variability in the ocean, we add degree 1 terms to the GRACE coefficients instead of removing the corresponding signal from the altimetry. We adopt annual estimates of the geocenter motion from *Chen et al.* [1999] and convert them to degree 1 gravity coefficients. We re-compute the water mass variations including these degree 1 terms and compare the differences.

3. Discussion of Results

[11] Figure 1 shows the time-series of ocean mass variations measured directly by GRACE without the geocenter estimates, along with that derived from the steric-corrected altimetry. Figure 2 shows the same steric-corrected altimetry variation, but the GRACE measurements include the degree 1 estimates. The time-series have been arbitrarily biased so that the mean of an annual sinusoid is zero. Note that the GRACE measurements are the average over a specific month in a specific year (e.g., November, 2003), while the altimetry + steric measurements have been averaged over many years (e.g., mean of many Novembers). Although there are only 14 GRACE observations, the GRACE and steric-corrected altimetry measurements are in good agreement. There is a peak in late-Summer, early-Fall in both 2002 and 2003, as well as a minimum in late-Winter early-Spring of 2003. By comparing Figure 2 to Figure 1, it is clear that the GRACE observations agree more closely with the steric-corrected altimetry climatology when the time-variable geocenter terms are included. The two data types (GRACE and steric-corrected altimetry) generally agree within the estimated error of the GRACE observations (see *Wahr et al.* [2004] for calculation).

[12] It is important to note that the seasonal GMSL signal does not exactly repeat every year. The total GMSL has interannual variations that often exceed the mean annual variation, especially during El Niño events [*Nerem et al.*, 1999]. When the 95% confidence level of the total GMSL is considered based on the standard deviation of the interannual fluctuations, one finds that the GRACE data and the 95% confidence interval of the mean signal from steric-corrected altimetry overlap in every case. Thus, the GRACE observations are entirely consistent with the mean seasonal ocean mass variation related to the global water cycle. Deviations are as likely to be caused by real interannual variations as by errors in the GRACE data.

[13] We have fit an annual sinusoid to both the GRACE and steric-corrected altimetry time-series in Figures 1 and 2. The sinusoid is defined so that the phase represents the time of the maximum from January 1. Table 1 lists the estimated amplitude and phase, along with the formal errors, which take into account the error bars and the reduced sampling of the GRACE measurements. The difference in amplitudes is 1.3 mm if degree 1 terms are not included with GRACE, but only 0.1 mm if geocenter variations are included. The phase, however, does change slightly when degree 1 variations are included, but within expected errors, and well within the sampling (1 month = 30°). If the GRACE data are averaged only between ±66°, neither the amplitude nor phase change significantly (Table 1). This indicates that there was no significant error in the altimetry - steric measurements due to non-global sampling, which was uncertain before. This is the first validation that GRACE is observing real ocean mass variations, at least on very large scales.

[14] Several previous studies of the seasonal ocean mass variability have examined closing the water mass budget by using the outputs of climate and hydrology models over land, since the average of the land + atmosphere water mass signal should be exactly out of phase with the ocean mass variation [*Chen et al.*, 1998; *Cazenave et al.*, 2000; *Milly et al.*, 2003]. The results of the previous studies are reproduced in Table 2. Overall, the agreement with the GRACE results is quite good, although there are still significant differences in both the amplitude and phase that likely reflect errors in the hydrologic models. This study, therefore, also validates the accuracy of the steric-corrected altimetry observation of the mean seasonal ocean mass variation, and further supports that there are still discrep-

Table 1. Estimated Annual Amplitude and Phase of Global Ocean Mass Variations From This Study[a]

Measurement Source	Amplitude (mm)	Phase (°)
Steric-corrected altimetry	8.5 ± 0.7	278 ± 5
GRACE (no degree 1)	7.2 ± 1.1	284 ± 8
GRACE (degree 1)	8.4 ± 1.1	266 ± 8
GRACE (degree 1), ±66°	8.6 ± 1.1	265 ± 8

[a]Errors are formal errors based on the individual error bars and number of points in the time-series. Phase is defined in degrees from January 1 using a cos(wt-phi) definition.

Table 2. Annual Amplitude and Phase of Global Ocean Mass Variations Determined From Hydrology Models or GPS[a]

Measurement Source	Amplitude (mm)	Phase (°)
Chen et al. [1998] Model 1	5.9	231
Chen et al. [1998] Model 2	8.9	302
Cazenave et al. [2000]	9.0	250
Milly et al. [2003] LaD	9.7	241
Milly et al. [2003] ISBA	9.4	260
GPS Loading [*Blewitt and Clarke*, 2003]	7.6	234

[a]Phase is defined consistently with Table 1.

ancies in the hydrology and climate models on global scales. An estimate of the annual variation in global mean ocean mass has also been derived from an analysis of the crustal motion due to loading for a global network of GPS sites [*Blewitt and Clarke*, 2003]. This technique effectively ''weighs the oceans'' by observing the motion of GPS sites attached to the Earth's crust. As shown in Table 2, this estimate agrees quite well with GRACE in terms of amplitude, but is different in phase by ~1 month.

4. Conclusions

[15] We have demonstrated that GRACE has observed the seasonal variation of global mean water mass into and out of the oceans, which was first observed using altimetry corrected for a steric variation. The two methods observe nearly the same seasonal signal once we correct for reference frame differences. The difference in amplitude is 0.1 mm and the difference in phase is only 12°. Our analysis corroborates the error estimates for the monthly GRACE data of about 1–2 mm of water thickness on global scales. Differences could also be explained by real interannual variations measured by GRACE.

[16] Although the determination of the mean seasonal ocean mass variation is not a unique result from GRACE, we expect that GRACE in the near future will contribute important new information to the Earth's global water cycle. For example, while the seasonal signal of the ocean mass variability can be determined accurately from altimetry and a steric model, it is difficult to obtain interannual variations due to the scarcity of ocean temperature and salinity observations. There is no reason to believe that GRACE should measure the low-frequency variations less accurately than the seasonal, although part of the long-term signal will be contaminated by post-glacial rebound (PGR). However, the use of a long-enough record and PGR models might allow us to determine low-frequency eustatic sea level change directly for the first time, which will be an important constraint on models used to predict global climate change. By combining satellite altimetry (which measures steric + eustatic variations) with GRACE (eustatic), the difference will also reveal the sea level change due to ocean heating. Understanding the relative contributions of steric and eustatic changes to sea level rise is an important goal of sea level change science.

[17] Additionally, GRACE observes time-variable mass over the continents. Preliminary calculations made over large continental discharge basins suggest that the accuracy of the GRACE measurements is at the level of a cm or less of water thickness [*Wahr et al.*, 2004]. Over larger continental regions, the accuracy will improve. Thus, in the near future we will be able to utilize GRACE alone to quantify how mass is exchanged between the continents and oceans, without having to rely on a combination of data and models, each with differing accuracies.

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References

Blewitt, G., and P. Clarke (2003), Inversion of Earth's changing shape to weigh sea level in static equilibrium with surface mass redistribution, *J. Geophys. Res.*, *108*(B6), 2311, doi:10.1029/2002JB002290.

Cazenave, A., F. Remy, K. Dominh, and H. Douville (2000), Global ocean mass variation, continental hydrology and the mass balance of Antarctica ice sheet at seasonal time scale, *Geophys. Res. Lett.*, *27*, 3755–3758.

Chambers, D. P., S. A. Hayes, J. C. Ries, and T. J. Urban (2003a), New TOPEX sea state bias models and their effect on global mean sea level, *J. Geophys. Res.*, *108*(C10), 3305, doi:10.1029/2003JC001839.

Chambers, D. P., J. C. Ries, and T. J. Urban (2003b), Calibration and verification of Jason-1 using global along-track residuals with TOPEX, *Mar. Geod.*, *26*, 305–318.

Chen, J. L., C. R. Wilson, D. P. Chambers et al. (1998), Seasonal global water mass balance and mean sea level variations, *Geophys. Res. Lett.*, *25*, 3555–3558.

Chen, J. L., C. R. Wilson, R. J. Eanes, and R. S. Nerem (1999), Geophysical interpretation of observed geocenter variations, *J. Geophys. Res.*, *104*, 2683–2690.

Jayne, S. R., J. M. Wahr, and F. O. Bryan (2003), Observing ocean heat content using satellite gravity and altimetry, *J. Geophys. Res.*, *108*(C2), 3031, doi:10.1029/2002JC001619.

Levitus, S., J. L. Antonov, T. P. Boyer, and C. Stephens (2000), Warming of the world ocean, *Science*, *287*, 2225–2229.

Milly, P. C. D., A. Cazenave, and M. C. Gennero (2003), Contribution of climate-driven change in continental water storage to recent sea-level rise, *Proc. Nat. Acad. Sci. U. S. A.*, *100*(23), 13,158–13,161.

Minster, J. F., A. Cazenave, and P. Rogel (1999), Annual cycle in mean sea level from Topex-Poseidon and ERS-1: Inference on the global hydrological cycle, *Global Planet. Change*, *20*, 57–66.

Nerem, R. S. (1995), Measuring global mean sea level variations using TOPEX/POSEIDON altimeter data, *J. Geophys. Res.*, *100*(C12), 25,135–25,151.

Nerem, R. S., D. P. Chambers, E. Leuliette et al. (1999), Variations in global mean sea level associated with the 1997–1998 ENSO event: Implications for measuring long-term sea level change, *Geophys. Res. Lett.*, *26*, 3005–3008.

Stephens, J. I., T. P. Antonov, T. P. Boyer et al. (2002), *World Ocean Atlas 2001*, vol. 1, *Temperatures*, *NOAA Atlas NESDIS 49*, edited by S. Levitus, 176 pp., U. S. Govt. Print. Office, Washington, D. C.

Swenson, S., and J. Wahr (2002), Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity, *J. Geophys. Res.*, *107*(B9), 2193, doi:10.1029/2001JB000576.

Tapley, B. D., S. Bettadpur, M. Watkins, and C. Reigber (2004), The Gravity Recovery and Climate Experiment: Mission overview and early results, *Geophys. Res. Lett.*, *31*, L09607, doi:10.1029/2004GL019920.

Wahr, J. (1985), Deformation induced by polar motion, *J. Geophys. Res.*, *90*, 9363–9368.

Wahr, J., M. Molenaar, and F. Bryan (1998), Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, *J. Geophys. Res.*, *103*, 30,229–32,205.

Wahr, J., S. Swenson, V. Zlotnicki, and I. Velicogna (2004), Time-variable gravity from GRACE: First results, *Geophys. Res. Lett.*, *31*, L11501, doi:10.1029/2004GL019779.

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